

MICROMECHANICAL DEVICE WITH DAMPED MICROACTUATOR

Inventors: John D. Grade
John H. Jerman
Joseph D. Drake

CROSS-REFERENCE TO RELATED APPLICATION

The application claims priority to U.S. provisional patent application Serial No. 60/209,558 filed June 6, 2000, the entire content of which is incorporated herein by this reference.

5 SCOPE OF THE INVENTION

The present invention relates generally to micromechanical devices and more particularly to damped micromechanical devices.

BACKGROUND

10 Micromechanical devices have heretofore been provided, and include sensors such as accelerometers, angular rate sensors and gyroscopes and optical devices such as optical switches, scanners, interferometers and tunable filters. Each of such devices includes a moving structure supported by flexural elements and is thus a spring mass system having one or more mechanical resonant modes. These modal frequencies are typically estimated through the use of finite element analysis. A mechanical quality factor or Q , which is a measure of the damping associated with the motion of the part, can be associated with each of these resonant modes.

15 For micromechanical devices fabricated in materials such as silicon, silicon dioxide, silicon nitride, or metals such as aluminum or nickel, the inherent damping of the structural material itself is extremely low. For example, electrostatic microactuators manufactured using deep reactive ion etched (DRIE) techniques often have comb gaps on the order of ten microns and thus do not provide damping in air that is sufficient for using such microactuators as positionable actuators. As a result, such devices typically have measurements of the mechanical quality factor Q in a vacuum that are typically greater than 5,000 and are potentially susceptible to external vibration or shock, especially from disturbances closely matching the frequency of one of the mechanical resonant modes of the device. It is thus important to control the damping of micromechanical devices.

25 Although viscous damping of micromechanical devices occurs from the dissipation of

energy resulting from the motion of fluid, such as air or liquid, in which the device resides, attempts to control the damping of such devices have been limited. For devices which operate at or near a mechanical resonance, such as some vibrational gyroscopes, it has been desirable to maximize the mechanical quality factor Q of the system by devising methods to package the devices in vacuum, thereby reducing the viscous damping due to air. Papers describing the effects of primarily air damping on a variety of micromechanical devices include: "Viscous Energy Dissipation in Laterally Oscillating Planar Microstructures: A Theoretical and Experimental Study", by Y.-H. Cho, et. al., 1993 Proceedings IEEE Micro Electro Mechanical Systems Workshop, Feb, 1993, pp. 93-98, and "Evaluation of Energy Dissipation Mechanisms in Vibrational Microstructures", by H. Hosaka, et. al., 1994 Proceedings IEEE Micro Electro Mechanical Systems Workshop, Feb. 1994, pp. 193-195. Neither of these papers, however, contains recommendations for modifying the geometry or fluid properties to optimize the damping of a device.

Some micromechanical devices, such as sensors, have relatively limited mechanical motion and can thus be controlled by including structures with small gaps, typically on the micron scale, in the device. In this technique, called squeeze-film damping, motion of the part causes such a gap to open and close, resulting in a fluid such as air flowing in and out of the gap. One of the many papers describing the use of holes through a structure to modify the squeeze-film effect is "Circuit Simulation Model of Gas Damping in Microstructures with Nontrivial Geometries", by T. Veijola, et. al., Proceedings of the 9th Int. Conference on Solid-State Sensors and Actuators, Stockholm, June, 1995, pp. 36-39. Unfortunately, squeeze-film damping is not generally suitable for devices having greater than a few microns of motion.

A limited amount of work has been done with linear accelerometers by packaging them in a viscous liquid, such as a silicone oil, to minimize "ringing" caused by the response of the accelerometer to shock. The practical issues involved with using fluids other than air to control or adjust damping in micromechanical devices have been discussed. See, for example, "A Batch-Fabricated Silicon Accelerometer", by Lynn Roylance, IEEE Trans. Elec. Dev., Vol. ED-26, Dec., 1979, pp1911-1917. See also International Application No. PCT/N092/00085 having International Publication No. WO 92/20096 by T. Kvisteroy et al. entitled "Arrangement for Encasing a Functional Device, and a Process for the Production of the Same". Neither of these publications, however, discuss the damping of actuators.

There is a need for a damped actuator. Unfortunately, none of the foregoing techniques has been used with actuators, and specifically with electrostatic actuators.

In general, it is an object of the present invention to provide a microactuator which is damped so as to control the resonant modes of the microactuator.

5 Another object of the invention is to provide a microactuator of the above character which is damped with a fluid other than air.

Another object of the invention is to provide a microactuator of the above character which is damped with a dielectric fluid.

10 Another object of the invention is to provide a microactuator of the above character which is damped with a liquid.

SUMMARY OF THE INVENTION

15 The present invention provides a damped micromechanical device comprising a housing having an internal fluid-tight chamber and an electrically-driven microactuator disposed in the fluid-tight chamber. The microactuator has a movable structure capable of being moved between first and second positions at a resonant frequency. A damping fluid is disposed in the fluid-tight chamber for damping the movement of the movable structure at the resonant frequency.

BRIEF DESCRIPTION OF THE DRAWINGS

20 The accompanying drawings, which are somewhat schematic in some instances and are incorporated in and form a part of this specification, illustrate an embodiment of the invention and, together with the description, serve to explain the principles of the invention.

FIG. 1 is a perspective view of a micromechanical device with damped microactuator of the present invention .

FIG. 2 is a perspective view of the micromechanical device of FIG. 1 with the cover removed to show the microactuator therein.

25 FIG. 3 is a top plan view of the microactuator in the micromechanical device of FIG. 1.

FIG. 4 is a cross-sectional view of the microactuator of FIG. 3 taken along the line 4-4 of FIG. 3.

FIG. 5 is a graph of the normalized rotation of the microactuator of FIG. 3 as a function of the operation frequency for several embodiments of the micromechanical device of FIG. 1.

DESCRIPTION OF THE INVENTION

The micromechanical device of the present invention can be in the form of a device or package 9 having any suitable housing 11 provided with an internal fluid-tight chamber 12. A microactuator, and preferably an electrically-driven microactuator 13, is disposed in the chamber 12 (see FIGS. 1 and 2). A damping fluid 16 is disposed in the chamber 12 for reducing movements of the movable portion of microactuator 13 at the resonant frequency of the microactuator.

Package 9 can preferably be similar to any of the conventional packages utilized for housing integrated circuits and other semiconductor devices. One embodiment of the package 9 is shown in FIGS. 1 and 2 and is similar to a conventional dual-inline integrated circuit package. Specifically, the housing 11 of package 9 has a main body 17 formed from any suitable material such as ceramic. Internal chamber 12 is formed in body 17, which has opposite first and second end portions 17a and 17b and is shown as having the shape of a parallelepiped. The body 17 has a planar top surface 18 interconnecting first and second opposite sides surfaces 19 and further includes a front surface 22 extending substantially perpendicular to surfaces 18 and 19. Chamber 12 extends downwardly from an opening 23 provided in top surface 18 and is formed, in part, by a forward surface 26 and a bottom surface 27. The forward surface 26 extends parallel to front surface 22 and perpendicular to bottom surface 27. A seal in the form of conventional sealing ring 28 is adhered or otherwise secured to top surface 18 around opening 23. The sealing ring 28 is made from any suitable materials such as gold.

Housing 11 further includes a cover 31 made from any suitable materials such as gold-plated Kovar. The cover sealably engages body 17, by means of sealing ring 28, at opening 23. Cover 31 or lid is preferably planar in conformation and extends over the ring 28 and opening 23. A corrugated-like flexible ring 32 is formed in cover 31 for providing a central portion 33 which can move inwardly and outwardly relative to opening 23 so as to accommodate expansion and compression of the fluid within the chamber 12. Lid 31 is secured to sealing ring 28 by any suitable means such as heat bonding.

Electrical interconnect means is included in package 9 for permitting electrical connections to be made with microactuator 13 carried within. In the illustrated embodiment of the package 9, such electrical interconnect means includes a plurality of conventional pins 36 spaced along each side surface 19 of body 17. Specifically, four pins 36 are provided on each

side surface 19. It should be appreciated that the invention is broad enough to cover solder bumps and any other conventional means of the packaged integrated circuit art for making electrical contact with microactuator 13. Each pin 36 is electrically interconnected, for example by means of internal electrical leads (not shown), to a respective interconnect or bonding pad 37 disposed within chamber 12. In the embodiment illustrated, a plurality of spaced-apart bonding pads 37 are provided on bottom surface 27 within chamber 12.

The electrically-driven microactuator 13 can be of any suitable type and is preferably an electromagnetic microactuator in which the movable portion of the microactuator is driven by electromagnetic forces. More preferably, the microactuator 13 is an electrostatic microactuator in which the movable portion of the microactuator is driven by electrostatic forces. Such electrostatic microactuator 13, in general, has similarities to the microactuators disclosed in U.S. patent application Serial No. 09/464,361 filed December 15, 1999 (Our file No. A-68185), U.S. patent application Serial No. 09/547,698 filed April 12, 2000 (Our file No. A-68187), U.S. patent application Serial No. 09/727,794 filed November 29, 2000 (Our file No. A-70055) and U.S. patent application Serial No. 09/755,743 filed January 5, 2001 (Our file No. A-70217), the entire content of each of which is incorporated herein by this reference. In this regard, microactuator 13 is formed on a planar substrate 41 and has a movable structure 42, which includes a mirror holder 43, that overlies substrate 41 (see FIGS. 3 and 4). At least one and as shown a plurality of first and second comb drive assemblies 46 and 47 are carried by substrate 41 for preferably rotating movable structure 42 in first and second opposite directions about an axis of rotation 48 extending perpendicular to planar substrate 41. The axis of rotation is shown as a point in FIG. 3 and labeled by reference line 48. Each of the first and second comb drive assemblies 46 and 47 includes a first drive member or comb drive member 51 mounted on substrate 41 and a second drive member or comb drive member 52 overlying the substrate. The movable structure 42 of rotary microactuator 13 includes second comb drives 52 and is supported or suspended above substrate 41 by first and second spaced-apart springs 43 and 44.

Substrate 41 is made from any suitable material such as silicon and is preferably formed from a silicon wafer. The substrate has a thickness ranging from 200 to 600 microns and preferably approximately 400 microns. Movable structure 42 and first and second springs 53 and 54 are formed atop the substrate 41 by a second or top layer 56 made from a wafer of any suitable material such as silicon (see FIG. 4). Top wafer 56 has a thickness ranging from 10 to

200 microns and preferably approximately 85 microns and is secured to substrate 41 by any suitable means. The top wafer is preferably fusion bonded to the substrate by means of a silicon dioxide layer 57, which further serves as an insulator between the conductive top wafer 56 and the conductive substrate 41. Top wafer 56 may be lapped and polished to the desired thickness.

5 Movable structure 32 and first and second springs 53 and 54 are formed from top wafer 56 by any suitable means, and are preferably etched from the wafer 56 using deep reactive ion etching techniques. The movable structure 42 and springs 53 and 54 are spaced above substrate 41 by an air gap 58, shown in FIG. 4, that ranges from three to 30 microns and is preferably approximately 15 microns, so as to be electrically isolated from the substrate 41.

10 At least one and preferably a plurality of first comb drive assemblies 46 are included in rotary electrostatic microactuator 13 and disposed about axis of rotation 48 for driving movable structure 42 in a clockwise direction about the axis of rotation 48. At least one and preferably a plurality of second comb drive assemblies 47 are included in microactuator 13 for driving movable structure 42 in a counterclockwise direction about the axis of rotation 48. Each of the
15 first and second comb drive assemblies 46 and 47 extends substantially radially from axis of rotation 48 and the assemblies 46 and 47, in the aggregate, subtend an angle ranging from 90 to 180 degrees and preferably approximately 180 degrees to provide a semicircular or fan-like shape to the microactuator 13. More particularly, microactuator 13 has three first comb drive assemblies 46a, 46b, and 46c and three second comb drive assemblies 47a, 47b, and 47c. The
20 rotary microactuator 13 has a base 61 extending along a diameter of the semicircle formed by the microactuator and a substantially semicircular-shaped arc 62 forming the outer periphery of microactuator 13. A radial centerline 63 extends in the plane of substrate 41 perpendicular to base 61 and through axis of rotation 48. The first comb drive assemblies 46 are interspersed between the second comb drive assemblies 47, and the first comb drive assemblies 46 are
25 symmetrically disposed relative to the second comb drive assemblies 47 about radial centerline 63. Mirror holder 43 is disposed at the center of microactuator 13 adjacent base 61.

First comb drive 51 of each of first and second comb drive assemblies 46 and 47 is mounted to substrate 41 by means of silicon dioxide layer 57. The first or stationary comb drives 51 are thus immovably secured to the substrate 41 and part of the stationary structure of
30 microactuator 13. Each of the first comb drives 51 has a radial-extending bar 66 provided with a first or inner radial portion and a second or outer radial portion. Such stationary bars 66 each

extend to the outer periphery 62 of the microactuator 13. A plurality of comb drive fingers or comb fingers 67 extend from one side of each bar 66 in longitudinally spaced-apart positions along the length of the bar at separation distances ranging from eight to 50 microns and preferably approximately 35 microns. First or movable comb fingers 67 extend substantially
5 perpendicularly from bar 66 and are each preferably arcuate in shape. In a preferred embodiment, piecewise linear segments are used to form the comb fingers 67 for approximating such an arcuate shape. Comb fingers 67 have a length ranging from 25 to 190 microns and increase substantially linearly in length from the inner portion to the outer portion of the bar 66. The comb fingers 67 can have a constant width along their length or vary in width along their
10 length. For example, the comb fingers of first comb drive assembly 46a have a constant width along their length, while the comb fingers 67 of first comb drive assemblies 46b and 46c have a proximal portion formed with a width ranging from four to 20 microns and preferably approximately 10 microns and a distal portion formed with a width less than such proximal portion and, more specifically, ranging from two to 12 microns and preferably approximately six
15 microns. Similarly, comb fingers 67 of the first or stationary comb drives 51 of second comb drive assemblies 47a and 47b have a proximal portion which is wider than the distal portion thereof, while comb fingers 67 of the first comb drive 51 of second comb drive assembly 47c are constant in width along the length thereof.

Second or movable comb drives 52 of each of first and second comb drive assemblies 46
20 and 47 are spaced above substrate 41 by air gap 58. The movable comb drives 52 each have a construction similar to the related first comb drive 51. In this regard, each of the movable comb drives 52 has a radially-extending bar 71 provided with a first or inner radial portion and a second or outer radial portion that extends to outer periphery 62 of the rotary electrostatic microactuator 13. A plurality of second comb drive fingers or comb fingers 72 extend from one
25 side of each of the bars 71 in longitudinally spaced-apart positions along the length of the bar. Second or movable comb drive fingers 72 are substantially similar to first or stationary comb drive fingers 67. Some of the second comb drive fingers have a constant width along the length thereof, for example, the second comb drive fingers of first comb drive assembly 46a and second comb drive assembly 47c, while the remaining second comb drive fingers have a width at their
30 proximal portion which is greater than the width at their distal portion. The second comb drive fingers 72 are offset relative to the first comb drive fingers 67 so that second comb drive fingers

72 can interdigitate with the first comb drive fingers 67 when each second comb drive 52 is moved closer to the respective first comb drive 51.

Bars 71 of second comb drive 52 are interconnected to form movable structure 42. In this regard, bar 71 of first comb drive assembly 46a and bar 71 of second comb drive assembly 47a are joined together at their outer radial end portions by an interconnecting member or link 76. Similarly, bar 71 of first comb drive assembly 46c and bar 71 of second comb drive assembly 47c are joined at their outer radial end portions by a link 76. The bars 71 of second comb drive assembly 47a and first comb drive assembly 46c are joined together at their inner radial end portions by mirror holder 43, which is preferably centered on radial centerline 63 adjacent axis of rotation 48. As such, the inner radial portions of such bars 71 are included within the means of microactuator 13 for coupling rotatable member or mirror holder 43 to second comb drives 52. Bars 71 of first comb drive assembly 46b and second comb drive assembly 46b are joined together by an interconnecting arcuate member 77 at the respective outer radial end portions.

First and second comb drive assemblies 46 and 47 have a length ranging from 200 to 2000 microns and preferably approximately 800 microns. The first and second comb drive assemblies do not all have to be of equal length. As shown in FIG. 3, first comb drive assembly 46b and second comb drive assembly 47b are substantially smaller in length than the remaining comb drive assemblies 46 and 47. At least one and as shown all of first and second comb drive assemblies 46 and 47 are not centered along a radial extending outwardly from axis of rotation 48. In this regard, the distal ends of the first and second comb fingers 67 and 72 of each comb drive assembly 46 and 47 are aligned along an imaginary line that does not intersect axis of rotation 48 and, instead, is spaced-apart from the axis of rotation 48. Each of the first and second comb drive assemblies 46 and 47 thus resembles a sector of a semicircle that is offset relative to a radial of such semicircle. It should nonetheless be appreciated that some or all of the first and second comb drive assemblies can be centered along a radial extending through axis of rotation 48.

Means including first and second spaced-apart springs 53 and 54 is included within microactuator 13 for movably supporting structure 42 over substrate 41 and for providing radial stiffness to the second comb drives 52 and mirror holder 43. Springs 53 and 54 are symmetrically disposed about radial centerline 63 and can have a length which approximates the length of at least some of first and second comb drive assemblies 46 and 47. A bracket member

or anchor 78 is provided along base 61 of microactuator 13 for coupling first and second springs 53 and 54 to the substrate 41. The inner radial end portions of first and second springs 53 and 54 are preferably joined to anchor 78 at axis of rotation 48. Each of the springs 53 and 54 is preferably a single beam-like member having a first or inner radial end portion joined to anchor 78, so as to be coupled to substrate 41, and a second or outer radial end portion joined to a link 76, so as to be coupled to second comb drives 52 and the remainder of removable structure 42. First spring 53 extends radially outwardly from anchor 78 between movable bars 71 of first comb drive assembly 46a and second comb drives assembly 47a and second spring 54 extends radially outwardly from the anchor between movable bars 71 of first comb drive assembly 46c and second comb drive assembly 47c. The springs 53 and 54 each have a width ranging from one ten microns and preferably approximately four microns.

Second comb drives 52 of first and second comb drive assemblies 46 and 47 are each movable in a direction of travel about axis of rotation 48 between a first or rest position, as shown in FIG. 3, in which the comb fingers 67 and 72 are not substantially fully interdigitated and a second position (not shown) in which the comb fingers 67 and 72 are substantially interdigitated. Comb drive fingers 67 and 72 can be partially interdigitated, as shown with first comb drive assemblies 46b and 46c and second comb drive assemblies 47a and 47b, or fully disengaged and thus not interdigitated, as shown with first comb drive assembly 46a and second comb drive assembly 47b, when the second comb drives 52 are in their first position. When in their second position, movable comb drive fingers 72 of the second comb drives 52 extend between respective stationary comb drive fingers 67 of the first comb drives 51. Movable comb drive fingers 72 approach but preferably do not engage stationary bar 66 and similarly stationary comb drive fingers 67 approach but preferably do not engage movable bar 71.

Each of the second comb drives 52 is also movable from its first position in an opposite second direction to a third position, not shown, in which comb drive fingers 67 and 72 are spaced apart and fully disengaged. When each second comb drive 52 of the first comb drive assemblies 46 is in its second position, each second comb drive 52 of the second comb assemblies 47 is in its third position. Similarly, when each second comb drive 52 of the second comb drive assemblies 47 is in its second position, each second comb drive 52 of the first comb drive assemblies 46 is in its third position.

Each of stationary and movable comb drive fingers 67 and 72 is optionally inclined

relative to respective bars 66 and 71. That, is each such comb finger is joined to its respective bar at an oblique angle, as disclosed in U.S. patent application Serial No. 09/755,743 filed January 5, 2001, as opposed to a right angle. The inclination angle at which each comb drive finger 67 and 72 is joined to its respective bar 66 and 71, measured from a line extending normal to the bar, can range from zero to five degrees and is preferably approximately three degrees. Each movable comb drive finger 72 is further optionally offset relative to the midpoint between the adjacent pair of stationary comb drive fingers 67 between which such movable comb drive finger interdigitates when the second comb drive 52 is electrostatically attracted to the first comb drive 51, also as disclosed in U.S. patent application Serial No. 09/755,743 filed January 5, 2001. When each movable comb drive finger 72 moves to its second position between the adjacent pair of stationary comb drive fingers 67, the movable comb drive finger becomes centered relative to the midpoint between the adjacent pair of stationary comb drive fingers 67. The offset and inclination of stationary and movable comb drive fingers 67 and 72 serves to accommodate the slight radially-inward shift of the movable comb drive 52, resulting from the deflection and foreshortening of first and second springs 53 and 54, when movable structure 42 moves from its first position in which springs 53 and 54 are in a straightened position, as shown in FIG. 3, to its second position in which springs 53 and 54 are bent or deflected.

First and second pointers 81 extend radially outwardly from respective links 76 for indicating the angular position of movable structure about axis of rotation 48 on first and second scales 82 provided on substrate 41.

Electrical means is included for driving second or movable comb drives 52 between their first and second positions. Such electrical means can include a controller and voltage generator 86 electrically connected to a plurality of electrodes provided on substrate 41. Such electrodes include a ground or common electrode 87 electrically coupled to anchor 78 and thus second or movable comb drives 52, one or more first drive electrodes 88 coupled to the first or stationary comb drives 51 of first comb drive assemblies 46, and one or more second drive electrodes 89 coupled to the first or stationary comb drives 51 of second comb drive assemblies 47. A metal layer (not shown) made from aluminum or any other suitable material is provided on the top surface of top wafer 56 for creating the electrodes and any leads relating thereto. Electrodes 87-89 are electrically coupled to internal bonding pads 37 by any suitable means such as wires (not shown) and are thus electrically coupled to appropriate pins 36. Controller and voltage generator

86, typically not a part of package 9, is electrically coupled to the pins 36 and is shown schematically in FIG. 3.

Means in the form of a closed loop servo control can be included for monitoring the position of movable comb drives 52 and thus mirror holder 43. For example, controller 86 can determine the position of the movable comb drives 52 about axis of rotation 48 by means of a conventional algorithm included in the controller for measuring the capacitance between comb drive fingers 72 of the movable comb drives 52 and comb drive fingers 67 of the stationary comb drives 51. A signal separate from the drive signal to the comb drive members can be transmitted by controller 86 to the microactuator 13 for measuring such capacitance. Such a method does not require physical contact between the comb drive fingers 52 and 67. Alternatively, where microactuator 13 is used in an optical system, as in the instant application, a portion of the output optical energy coupled into the output fiber can be diverted and measured and the drive signal from the controller 86 to the microactuator 13 adjusted so that the measured optical energy is maximized.

The optical microswitch of package 9 is similar to the optical microswitch disclosed in U.S. patent application Serial No. 09/464,361 filed December 15, 1999. In this regard, a micromachined mirror 96 is coupled to microactuator 13 and extends out of the plane of the microactuator. More specifically, micromirror 96 is secured to microactuator 13 by a post preferably formed integral with the mirror 96 and micromachined separately from microactuator 13. The post is joined at its base to mirror holder 43 by any suitable means such as an adhesive. Micromirror 96 has a reflective face or surface 97 and is rotatable by microactuator 13 about axis of rotation 48.

Microactuator 13 is secured to bottom surface 27 of body 17 adjacent forward surface 26 by an adhesive or any other suitable means. Micromirror 96 extends substantially parallel to forward surface 26 and mirror face 97 faces the forward surface 26. An optically clear window can be provided in body 17 so that laser light can pass through front surface 22 and forward surface 26 and thus impinge on mirror face 97. Although a clear glass window can be utilized to couple the laser light into package 9, in the one preferred embodiment shown in FIGS. 1 and 2 a collimating lens such as a GRIN lens 98 is carried by body 17 to collimate the optical beam and to provide a fluid-tight seal between internal chamber 12 and the environment outside package 9. GRIN lens 98 is soldered or otherwise secured inside a tube formed integral with a

Kovar end plate 101 brazed to front surface 22 of package body 17. GRIN lens 98 has an outer surface 99 and an inner surface (not shown) that is spaced from mirror face 97 a distance equal to the focal distance of the lens 98.

A damping material or fluid is disposed within internal chamber 12 for damping the movement of movable structure 42 during the operation of optical switching package 9. One or more filling holes 103 are provided in body 17 and/or lid 31 for introducing the damping the fluid into chamber 12. As shown, a plurality of two filling holes 103 extend through body 17 and onto bottom surface 27. Filling holes 103 are preferably gold plated. In another embodiment of (not shown), a Kovar or other metal tube is provided in body 17 adjacent to GRIN lens 98. The tube is accessible at front surface 22 of package body 17 for filling internal chamber 12.

Damping fluid 16 is particularly suited for damping the movement of movable structure 42 and thus micromirror 96 carried thereby at the resonant frequency of such structures relative to the stationary structure of microactuator 13. Such resonant frequency is a function of the mechanical quality factor Q of the microactuator 13. If the dominant dissipation mechanism between stationary and movable comb drives or electrodes 51 and 52 is Couette flow, then such mechanical quality factor Q is inversely proportional to the viscosity of the damping fluid.

Although any suitable damping material can be utilized, a damping fluid is preferred. The viscosity of the damping fluid is chosen such that the mechanical quality factor Q of the microactuator 13, when immersed within the damping fluid in internal chamber 12, preferably ranges from 0.3 to 20 and more preferably ranges from 0.5 to three. When the mechanical quality factor Q is at such levels, undesired spikes in the rotational motion of the movable structure 42 of microactuator 13 are minimized.

A high-viscosity gas, a low-viscosity fluid or any suitable energy dissipating material can be used for damping microactuator 13. Preferred damping fluids have a viscosity greater than the viscosity of air. The viscosity of the damping fluid can be chosen over a range of at least four orders of magnitude, given reasonable ability to select the amount of damping required for a given structure of the actuator. In one preferred embodiment, the damping fluid is a liquid.

The damping fluid is preferably a dielectric fluid, that is a substantially insulating fluid, and is typically a dielectric liquid. Since the force produced by an electrostatic actuator is proportional to the magnitude of the dielectric constant of any fluid filling the gap between the

electrodes of the actuator, in this instance the gap between stationary comb drive fingers 67 and movable comb drive fingers 72, an increase in force of the microactuator can be provided by increasing the dielectric constant of the damping fluid. The relative dielectric constant of many dielectric fluids is many times greater than the dielectric constant of air, thus providing the same increase in force from a similar microactuator immersed in air for a given voltage and electrode geometry. The dielectric constant of the damping fluid is preferably greater than two and more preferably ranges from three to ten.

The damping fluid can be either a nonpolar fluid or a polar fluid. The dielectric constant of a fluid tends to increase with increasing polarity of the fluid. Hence, it can be advantageous to provide damping fluids, preferably damping liquids, with higher polarities. In another preferred embodiment, the damping fluid can be a super-critical fluid at the operational temperature of microactuator 13 and at the pressure in internal chamber 12 during such operation.

At least one optional drag-inducing member can be carried by movable structure 42 for producing drag on the movable structure as it moves between its first and third positions. In this regard, at least one and as shown a plurality of drag-inducing members or fins 106 are provided on arcuate member 77 of movable structure 42. Additional fins 106 are also provided at the outer radial end portions of movable bars 71 of first comb drive assembly 46b and second comb drive assembly 47b. Stationary drag-inducing members or fins 107 can optionally be mounted on substrate 41 in the vicinity of movable fins 106. As shown in FIG. 3, stationary fins 107 are disposed adjacent the movable fins 106 on arcuate member 77 and the outer radial end portions of such movable bars 71 discussed above. Fins 106 and 107 preferably extend substantially perpendicular to the direction of travel of movable structure 42 and are preferably disposed in the vicinity of each other. It is advantageous to minimize the mechanical clearance of fins 106 and 107 so as to maximize their effect. Such non-interdigitated fins can be provided which have sufficient clearance to be fabricated, yet as they move pass each other during motion of movable structure 42 the gap between such fins is less than the when-fabricated clearance between the fins. It should be appreciated that fins 106 and/or 107 can be provided at other locations on microactuator 13 and be of other shapes and sizes and be within the scope of the present invention. Furthermore, in other embodiments of the invention, such damping fins can be fabricated in structures which are not part of the electrostatic drive mechanisms of microactuator 13 such that a voltage difference does not exist between the movable and stationary fins when

microactuator 13 is being operated.

In operation and use, after fabrication of microactuator 13 and the attachment of micromirror 96 to mirror holder 43, the microactuator 13 is attached to bottom surface 27 in the manner discussed above. Lid 31 is attached to body 17 by means of sealing ring 28. Chamber 12 is filled with the appropriate damping fluid by means of filling holes 103 and the chamber 12 is then sealed by press fitting a plug, or soldering or welding a lid, to the exterior end of the filling holes 103. In the embodiment where a metal fill tube is provided adjacent GRIN lens 98, chamber 12 is filled by means of such tube with the damping fluid. The tube is then crimped or welded shut to contain the damping fluid within package 9.

Once package 9 is plugged into place or otherwise mounted into a suitable optical system, for example adjacent the ends of one or more optical fibers in a telecommunication system, and electrically coupled by means of pins 36 to a suitable controller and voltage generator 86, the package 9 can be used for switching laser light between the one or more optical fibers in the manner disclosed in U.S. patent application Serial No.09/464,373 filed December 15, 1999 (Our file No. A-68184), the entire content of which is incorporated herein by this reference. As part of this operation, mirror holder 43 can be rotated in opposite first and second directions of travel about axis of rotation 48 by controller 86. Suitable voltage potentials to first and second drive electrodes 88 and 89 can range from 20 to 250 volts and preferably range from 60 to 180 volts. Microactuator 13 is capable of +/- six degrees of angular rotation, that is a rotation of six degrees in both the clockwise and counterclockwise directions for an aggregate rotation of twelve degrees, when such drive voltages are utilized. Mirror holder 43, and thus micromirror 96, can be stopped and held at any location in such range of motion.

The utilization of a damping fluid within package 9 serves to damp the resonant modes of the microactuator 13. The rotation of movable structure 42 about axis of rotation 48 was studied as a function of the frequency of operation of microactuator 13. The graph in FIG. 5 plots the normalized rotation of movable structure of 42 as a function of frequency for several test cases. As set forth therein, an initial test of microactuator 13 was performed utilizing air as a damping fluid. The mechanical quality factor Q of microactuator 13 was calculated to be approximately 20 when operated in air, which has a viscosity at room temperature of approximately 190 uP. The microactuator 13 had an in-plane fundamental resonant frequency of 700 Hz and an out-of-plane resonant frequency of 2350 Hz when so tested in air. The

increased vibration amplitude at integer sub-harmonics of these resonances is due to the nonlinear nature of the drive force.

Microactuator 13 was then tested using several damping fluids having a viscosity greater than air. Specifically an immersion liquid sold by Cargille Laboratories of Cedar Grove, New Jersey, known as Cargille immersion liquid, Formula Code 4501, and diethylbenzene (DEB). The Cargille immersion liquid had a viscosity of 1.4 cP, as measured by a falling ball viscometer, and the diethylbenzene had a measured viscosity of 0.6 cP. Couette flow would predict a mechanical quality factor Q for microactuator 13 of approximately 0.25 in the Cargille fluid and a mechanical quality factor Q of approximately 0.60 in diethylbenzene, in each case neglecting the change in mass due to fluid motion. The resonant frequency for the Cargille fluid was calculated to be 375 Hz with a mechanical quality factor Q of 0.22 and the resonant frequency for the diethylbenzene was calculated to be 349 Hz with a mechanical quality factor of 0.66. After such test, package 9 was drained and microactuator or motor 13 was rinsed in isopropyl alcohol and dried. The frequency response of microactuator 13 was then measured again in air. As shown in FIG. 5, the utilization of such damping fluids in package 9 served to reduce the mechanical quality factor Q to an acceptable level and thus damp the microactuator 13 at its resonant modes.

As can be seen, when damping fluids with sufficient viscosity are utilized, the drag induced by the relative motion between the comb drive fingers 67 and 72 is sufficient to substantially damp the resonance of microactuator 13. In addition, since desired damping fluids are also denser than air, when movable structure 42 is immersed in the fluid, the inertial forces on the movable structure are reduced due to the buoyancy of the movable structure in the fluid. For example, the inertial forces on movable structure 42 made from silicon, which has a density of approximately 2.3 gm/cc, are reduced by approximately eighty percent when the structure 42 is immersed in a damping fluid such as perfluorodecalin having a density of approximately 1.92 gm/cc.

Other suitable damping fluids, not identified on FIG. 5, include neon, d-limonene, octamethyltrisiloxane, t-octylamine and ethoxy-nonafluorobutane. Neon, which has a viscosity at room temperature of approximately 315 uP, compared to the 190 uP viscosity of air at room temperature, is particularly suitable if only a small increase in damping is required for microactuator 13 or another micromechanical device. If a small decrease in damping is desired,

for example with parts where squeeze-film damping predominates, the use of hydrogen with a viscosity of approximately 90 uP is suitable.

The relative dielectric constant of the fluid was calculated by taking the square of the ratio of voltages required to achieve 50% of the full deflection at low frequency. The Cargille immersion liquid had a dielectric constant ϵ of 2.44 and diethylbenzene had a dielectric constant ϵ of 3.45. The Cargille immersion liquid thus provided an increase in microactuator force of approximately 2.44 and diethylbenzene provided an increase in microactuator force of approximately 3.45, in each case, relative to the force produced by microactuator 13 when operated in air.

Optional fins 106 and 107 provide additional drag on movable structure 42 so as to further damp the resonant modes of the movable structure 42 during operation of microactuator 13 and optical package 9. As movable fins 106 pass stationary fins 107, increased fluid flow is provided in internal chamber 12. Specifically, fins 106 and 107 increase the turbulence of the fluid flow within chamber 12 and thus increase the drag on movable structure 42.

Although the fluid-damped microactuator of the present invention has been shown as being part of a optical microswitch, it should be appreciated that a fluid-damped microactuator can be provided in a variety of other optical components. Further, a fluid-damped microactuator of the present invention can be utilized in other than telecommunications systems. For example, such microactuators can be utilized in data storage systems, for example magneto optical data storage systems. It should also be appreciated that the drag-inducing members of the present invention can be used in undamped microactuators, for example microactuators or other microdevices operated in air. The damping techniques disclosed herein can be used in combination with the damping techniques disclosed in U.S. patent application Serial No. _____ filed contemporaneously herewith (Our file No. A-70529), the entire content of which is incorporated herein by this reference. In addition, the damping fluids hereof can also be used with devices other than actuators.

As can be seen from the foregoing, a microactuator has been provided which is damped so as to control the resonant modes of the microactuator. The microactuator is damped with a fluid other than air and is preferably damped with a dielectric fluid. Nonpolar or polar fluids can be used as the damping fluid. The damping fluid can be any suitable liquid. The damped microactuator hereof is suited for moving structures throughout a broad range of motion to a

variety of locations, and holding such structures at such locations, particularly in the presence of vibration or other disturbances at or near the resonance frequency.

11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000
1001
1002
1003
1004
1005
1006
1007
1008
1009
1010
1011
1012
1013
1014
1015
1016
1017
1018
1019
1020
1021
1022
1023
1024
1025
1026
1027
1028
1029
1030
1031
1032
1033
1034
1035
1036
1037
1038
1039
1040
1041
1042
1043
1044
1045
1046
1047
1048
1049
1050
1051
1052
1053
1054
1055
1056
1057
1058
1059
1060
1061
1062
1063
1064
1065
1066
1067
1068
1069
1070
1071
1072
1073
1074
1075
1076
1077
1078
1079
1080
1081
1082
1083
1084
1085
1086
1087
1088
1089
1090
1091
1092
1093
1094
1095
1096
1097
1098
1099
1100
1101
1102
1103
1104
1105
1106
1107
1108
1109
1110
1111
1112
1113
1114
1115
1116
1117
1118
1119
1120
1121
1122
1123
1124
1125
1126
1127
1128
1129
1130
1131
1132
1133
1134
1135
1136
1137
1138
1139
1140
1141
1142
1143
1144
1145
1146
1147
1148
1149
1150
1151
1152
1153
1154
1155
1156
1157
1158
1159
1160
1161
1162
1163
1164
1165
1166
1167
1168
1169
1170
1171
1172
1173
1174
1175
1176
1177
1178
1179
1180
1181
1182
1183
1184
1185
1186
1187
1188
1189
1190
1191
1192
1193
1194
1195
1196
1197
1198
1199
1200
1201
1202
1203
1204
1205
1206
1207
1208
1209
1210
1211
1212
1213
1214
1215
1216
1217
1218
1219
1220
1221
1222
1223
1224
1225
1226
1227
1228
1229
1230
1231
1232
1233
1234
1235
1236
1237
1238
1239
1240
1241
1242
1243
1244
1245
1246
1247
1248
1249
1250
1251
1252
1253
1254
1255
1256
1257
1258
1259
1260
1261
1262
1263
1264
1265
1266
1267
1268
1269
1270
1271
1272
1273
1274
1275
1276
1277
1278
1279
1280
1281
1282
1283
1284
1285
1286
1287
1288
1289
1290
1291
1292
1293
1294
1295
1296
1297
1298
1299
1300
1301
1302
1303
1304
1305
1306
1307
1308
1309
1310
1311
1312
1313
1314
1315
1316
1317
1318
1319
1320
1321
1322
1323
1324
1325
1326
1327
1328
1329
1330
1331
1332
1333
1334
1335
1336
1337
1338
1339
1340
1341
1342
1343
1344
1345
1346
1347
1348
1349
1350
1351
1352
1353
1354
1355
1356
1357
1358
1359
1360
1361
1362
1363
1364
1365
1366
1367
1368
1369
1370
1371
1372
1373
1374
1375
1376
1377
1378
1379
1380
1381
1382
1383
1384
1385
1386
1387
1388
1389
1390
1391
1392
1393
1394
1395
1396
1397
1398
1399
1400
1401
1402
1403
1404
1405
1406
1407
1408
1409
1410
1411
1412
1413
1414
1415
1416
1417
1418
1419
1420
1421
1422
1423
1424
1425
1426
1427
1428
1429
1430
1431
1432
1433
1434
1435
1436
1437
1438
1439
1440
1441
1442
1443
1444
1445
1446
1447
1448
1449
1450
1451
1452
1453
1454
1455
1456
1457
1458
1459
1460
1461
1462
1463
1464
1465
1466
1467
1468
1469
1470
1471
1472
1473
1474
1475
1476
1477
1478
1479
1480
1481
1482
1483
1484
1485
1486
1487
1488
1489
1490
1491
1492
1493
1494
1495
1496
1497
1498
1499
1500
1501
1502
1503
1504
1505
1506
1507
1508
1509
1510
1511
1512
1513
1514
1515
1516
1517
1518
1519
1520
1521
1522
1523
1524
1525
1526
1527
1528
1529
1530
1531
1532
1533
1534
1535
1536
1537
1538
1539
1540
1541
1542
1543
1544
1545
1546
1547
1548
1549
1550
1551
1552
1553
1554
1555
1556
1557
1558
1559
1560
1561
1562
1563
1564
1565
1566
1567
1568
1569
1570
1571
1572
1573
1574
1575
1576
1577
1578
1579
1580
1581
1582
1583
1584
1585
1586
1587
1588
1589
1590
1591
1592
1593
1594
1595
1596
1597
1598
1599
1600
1601
1602
1603
1604
1605
1606
1607
1608
1609
1610
1611
1612
1613
1614
1615
1616
1617
1618
1619
1620
1621
1622
1623
1624
1625
1626
1627
1628
1629
1630
1631
1632
1633
1634
1635
1636
1637
1638
1639
1640
1641
1642
1643
1644
1645
1646
1647
1648
1649
1650
1651
1652
1653
1654
1655
1656
1657
1658
1659
1660
1661
1662
1663
1664
1665
1666
1667
1668
1669
1670
1671
1672
1673
1674
1675
1676
1677
1678
1679
1680
1681
1682
1683
1684
1685
1686
1687
1688
1689
1690
1691
1692
1693
1694
1695
1696
1697
1698
1699
1700
1701
1702
1703
1704
1705
1706
1707
1708
1709
1710
1711
1712
1713
1714
1715
1716
1717
1718
1719
1720
1721
1722
1723
1724
1725
1726
1727
1728
1729
1730
1731
1732
1733
1734
1735
1736
1737
1738
1739
1740
1741
1742
1743
1744
1745
1746
1747
1748
1749
1750
1751
1752
1753
1754
1755
1756
1757
1758
1759
1760
1761
1762
1763
1764
1765
1766
1767
1768
1769
1770
1771
1772
1773
1774
1775
1776
1777
1778
1779
1780
1781
1782
1783
1784
1785
1786
1787
1788
1789
1790
1791
1792
1793
1794
1795
1796
1797
1798
1799
1800
1801
1802
1803
1804
1805
1806
1807
1808
1809
1810
1811
1812
1813
1814
1815
1816
1817
1818
1819
1820
1821
1822
1823
1824
1825
1826
1827
1828
1829
1830
1831
1832
1833
1834
1835
1836
1837
1838
1839
1840
1841
1842
1843
1844
1845
1846
1847
1848
1849
1850
1851
1852
1853
1854
1855
1856
1857
1858
1859
1860
1861
1862
1863
1864
1865
1866
1867
1868
1869
1870
1871
1872
1873
1874
1875
1876
1877
1878
1879
1880
1881
1882
1883
1884
1885
1886
1887
1888
1889
1890
1891
1892
1893
1894
1895
1896
1897
1898
1899
1900
1901
1902
1903
1904
1905
1906
1907
1908
1909
1910
1911
1912
1913
1914
1915
1916
1917
1918
1919
1920
1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070
2071
2072
2073
2074
2075
2076
2077
2078
2079
2080
2081
2082
2083
2084
2085
2086
2087
2088
2089
2090
2091
2092
2093
2094
2095
2096
2097
2098
2099
2100
2101
2102
2103
2104
2105
2106
2107
2108
2109
2110
2111
2112
2113
2114
2115
2116
2117
2118
2119
2120
2121
2122
2123
2124
2125
2126
2127
2128
2129
2130
2131
2132
2133
2134
2135
2136
2137
2138
2139
2140
2141
2142
2143
2144
2145
2146
2147
2148
2149
2150
2151
2152
2153
2154
2155
2156
2157
2158
2159
2160
2161
2162
2163
2164
2165
2166
2167
2168
2169
2170
2171
2172
2173
2174
2175
2176
2177
2178
2179
2180
2181
2182
2183
2184
2185
2186
2187
2188
2189
2190
2191
2192
2193
2194
2195
2196
2197
2198
2199
2200
2201
2202
2203
2204
2205
2206
2207
2208
2209
2210
2211
2212
2213
2214
2215
2216
2217
2218
2219
2220
2221
2222
2223
2224
2225
2226
2227
2228
2229
2230
2231
2232
2233
2234
2235
2236
2237
2238
2239
22